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EXTRACTION OF SPECTRAL LINES FROM SEISMIC DATA

Technical Report No. 1

SEISMIC ARRAY PROCESSING TECHNIQUES

Prepared by

Martin Lichtenstein

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TEXAS INSTRUMENTS INCORPORATED
Services Group
P.O. Box 5621
Dallas, Texas 75222

Contract No. F33657-70-C-0100
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Beginning 15 July 1969
Ending 14 July 1970

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C. 20333

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15 January 1970

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ABSTRACT

Two methods for the removal in real time of stable spectral lines from seismic data were investigated. The first method involved the generation of a cosine wave, by means of a digital feedback system, to approximate a spectral line. In this method, the cosine generator is adjusted in accordance with a mean-square-error criterion. This system of adjustment was simulated and proved to be unstable. In the second method, a Widrow adaptive prediction filter is used to remove the deterministic component. A simulation of this prediction method was carried out using one seismic data channel from a short-period array. Results show that this method significantly attenuates some of the spectral lines. However, if a signal were present, some amplitude and phase distortion would be caused in the signal. In addition, this system would be cumbersome to implement.

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SECTION I
INTRODUCTION AND SUMMARY

This report discusses the removal of stable spectral lines from seismic data in real time. The source of these lines is suspected to be mining, drilling, or other man-made activity. At some stations, these spectral lines are of relatively high energy and are present in the band of strong signal energy. Because the exact frequency of each line is not known, and because these frequencies may slowly fluctuate, a single fixed filter with appropriately positioned nulls may not be effective. Furthermore, it would be difficult to implement such a fixed filter to obtain a relatively distortion-free response over the remaining spectrum.

A time-domain technique for predicting extremely narrow spectral line components, so that they may be removed by subtraction, has been demonstrated in a previous report.* This technique has been shown to be highly effective, and its use would be most beneficial at stations having narrow spectral lines in the ambient noise at frequencies in the signal band. However, this technique involved designing an optimum 100-point linear prediction filter from over 2000 points of data and would be relatively difficult to implement. The problem investigated in this report is to find a simplified method which would be suitable for real-time processing. If such a method works, the spectral lines in the output data should be greatly attenuated in comparison to the input data, and the rest of the frequency spectrum should be relatively undistorted.

Two methods for the removal of spectral lines were studied. Assumed for each method are

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*Texas Instruments Incorporated, 1969: Analysis of the Wichita Mountains Seismological Observatory Ambient Noise Spectral Lines, Advanced Array Research Spec. Rpt. 10, Contract F33657-68-C-0867, 9 May.

- The data are the sum of two processes: a random, wide-band process and a relatively deterministic process
- The relatively deterministic process is that which gives rise to the spectral lines and can thus be predicted and removed from the data

A digital feedback system, called a cosine generator, is used in the first method to generate a cosine wave. The purpose is to approximate the spectral line by a generated cosine wave, and the cosine generator is adjusted in accordance with a mean-square-error criterion. This system of adjustment has been simulated and proves to be unstable.

In the second method, a Widrow adaptive prediction filter is used to remove the deterministic component. A simulation of this prediction method has been carried out using one seismic data channel from a short-period array. The results show that this method does attenuate significantly some of the spectral lines. However, some amplitude and phase distortion would be caused in a signal, if it were present. In addition, it would be cumbersome to implement this system.

SECTION II

METHOD 1: COSINE GENERATOR, MEAN-SQUARE-ERROR CRITERION

A. GENERAL DESCRIPTION

In this method, a digital feedback system is used to generate a sinusoid which is used to approximate a spectral line in the data. The error of the approximation is calculated and statistical parameters of the signal are estimated at regular intervals. These quantities are employed using a heuristic least mean-square-error criterion for adjusting the cosine generator. The scheme is heuristic in that certain functional dependences are neglected for simplicity.

Actual simulation shows this type of system to be unstable. It is expected that the neglected functional dependences cause this instability. Although these dependences were obvious, it was hoped that their presence would not adversely affect the proposed system.

B. ANALYSIS OF OPERATION

Let x_k be the input data, and r_k be the generated sinusoid. Then r_k is given by $r_k = B\,r_{k-1} - A\,r_{k-2}$. The error in approximating x_k with r_k is $\epsilon_k = x_k - r_k$. The squared error is given by

$$\epsilon_k^2 = \left[1,\ -B,\ A\right] \begin{bmatrix} x_k^2 & x_k r_{k-1} & x_k r_{k-2} \\ x_k r_{k-1} & r_{k-1}^2 & r_{k-1} r_{k-2} \\ x_k r_{k-2} & r_{k-1} r_{k-2} & r_{k-2}^2 \end{bmatrix} \begin{bmatrix} 1 \\ -B \\ A \end{bmatrix} \tag{2-1}$$

and the mean-squared- error is given by

$$\overline{\epsilon_k^2} = \left[1,\ -B,\ A\right] \begin{bmatrix} \overline{x_k^2} & \overline{x_k r_{k-1}} & \overline{x_k r_{k-2}} \\ \overline{x_k r_{k-1}} & \overline{r_{k-1}^2} & \overline{r_{k-1} r_{k-2}} \\ \overline{x_k r_{k-2}} & \overline{r_{k-1} r_{k-2}} & \overline{r_{k-2}^2} \end{bmatrix} \begin{bmatrix} 1 \\ -B \\ A \end{bmatrix} \tag{2-2}$$

If the sequence r_k were not functionally dependent on A, B, the quantities in the matrix of Equation 2-2 would not be determined by A, B. If this is assumed, A and B can be considered undetermined constants, and the mean-squared-error can be minimized by selecting

$$\begin{bmatrix} -B \\ A \end{bmatrix} = \begin{bmatrix} \overline{r_{k-1}^2} & \overline{r_{k-1}\, r_{k-2}} \\ \overline{r_{k-1}\, r_{k-2}} & \overline{r_{k-2}^2} \end{bmatrix} \begin{bmatrix} \overline{x_k\, r_{k-1}} \\ \overline{x_k\, r_{k-2}} \end{bmatrix} \tag{2-3}$$

Estimates of the covariances must be made to implement this system, and thus the system error and stability are sensitive to how these estimates are made. The covariance matrix of Equation 2-2 is named $\underline{R}$, and an estimate of it is made at regular intervals in accordance with the following relationship.

$$\underline{\hat{R}}_k = (1 - \epsilon)\underline{\hat{R}}_{k-1} + \epsilon \begin{bmatrix} x_k^2 & x_k\, r_{k-1} & x_k\, r_{k-2} \\ x_k\, r_{k-1} & r_{k-1}^2 & r_{k-1}\, r_{k-2} \\ x_k\, r_{k-2} & r_{k-1}\, r_{k-2} & r_{k-2}^2 \end{bmatrix} ; \; 0 < \epsilon < 1 \tag{2-4}$$

This method of estimation is effectively the same as computing the covariance matrix using data which is weighted by a decaying exponential function. The initial estimate $\underline{\hat{R}}_o$ is selected to be the identity matrix.

The oscillator is initialized to generate a sine wave. This is done by selecting $r_o = 0$, $r_1 = 1$, and $A = 1$. The coefficient B is set by the relationship

$$\frac{1}{2B} = \cos \varphi \qquad , \text{ where } \varphi = \pi \frac{\text{frequency of line}}{\text{folding frequency}}$$

In this relationship, the folding frequency is considered to be one-half the sampling frequency.

SECTION III

METHOD 2: WIDROW PREDICTION FILTER

This method uses a Widrow prediction filter to predict the sum of all the spectral lines in the data.* The filter is applied to the data, and the system output is formed by subtracting the prediction of the spectral lines from the input data. This output is thus constructed to approximate the input data minus the spectral lines. Because this output is the "error" between the prediction and actual data, this system is sometimes referred to as a "prediction-error filter".

A simulation of this prediction method for spectral line removal has been carried out using seismic data from a short-period array. The input data spectrum is shown in Figure III-1. A 20-point long prediction filter was adaptively designed to predict the data several points in the future. In applying the filter, several experiments were done using various prediction lengths. (The design parameter determining which point in the future to predict is referred to as the prediction length. For example, the 20-point filter operating on data points 1 through 20, and designed to predict data point 25, would have a prediction length of five. In operation, the error in prediction would be used to update the filter, and the filter would be applied to points 2 through 21, and the output would be the prediction of point 26.) Also, the rate of adaption, referred to as the convergence parameter, was changed, yielding a table of results. Specifically, the prediction lengths were 10, 50, 100, and 200 sample-points ahead and the filter convergence parameter k_s took on values of $0.005 \times k_{max}$, $0.05 \times k_{max}$, and $0.25 \times k_{max}$, where k_{max} is a theoretical limitation on the convergence factor. The output spectra are shown in Figures III-2 through III-12.

It is seen from Figure III-1 that by far the greatest proportion of energy from spectral lines occurs in those two lines between 2.5 and 3.0 Hz.

*Widrow, Bernard, 1966: Adaptive Filters I: Fundamental, Stanford University Tech. Rpt. No. 6764-6, Systems Theory Laboratory, Contract No. NOBsr-95038 and Contract No. DA-01-021 AMC-90015(Y), Dec.

Figure III-6 shows that these lines are attenuated by 13 db when the data are filtered with a prediction-error filter which predicts 50 points ahead with a convergence parameter equal to $0.05 \times k_{max}$. While other spectral lines are not significantly attenuated, it is noted that these lines contain relatively little energy in comparison to the larger two lines and the results were obtained on a comparatively short piece of data.

The data are 3300 points long (about 4 min) and the method used to filter it follows. The initial filter is chosen to be composed only of zeros. As the filter processes the first 1000 points of data, the convergence parameter k_s is decreased linearly to its final value. This new value is kept constant for the remainder of the processing in that trial. (The initial values of k_s depend upon the corresponding final values. For final values of $0.05\ k_{max}$ and $0.25\ k_{max}$, the initial value of k_s is twice these corresponding values. For the final value, $0.005\ k_{max}$, k_s was initially set to $0.5\ k_{max}$.)

To determine how much the prediction filter would distort a signal if a signal were present, the frequency response of several prediction filters were computed. Because the filters are adaptive, they change as they process each new point of data, and the terminal filters were selected for computing the frequency response. The responses appeared similar, and the response of the filter which produced the output spectrum shown in Figure III-6 is shown in Figure III-13. The relatively large amplitude response throughout the frequency spectrum, combined with a nonuniform phase response (not shown), indicate a considerable amount of distortion would occur in a signal if it were present.

In summary, the results do not indicate that all of the spectral lines are significantly attenuated. In addition, amplitude and phase distortion would be caused in a signal if it were present. Although results from processing a longer segment of data may show a more uniform attenuation of all spectral lines, the problem of signal distortion would still be present.

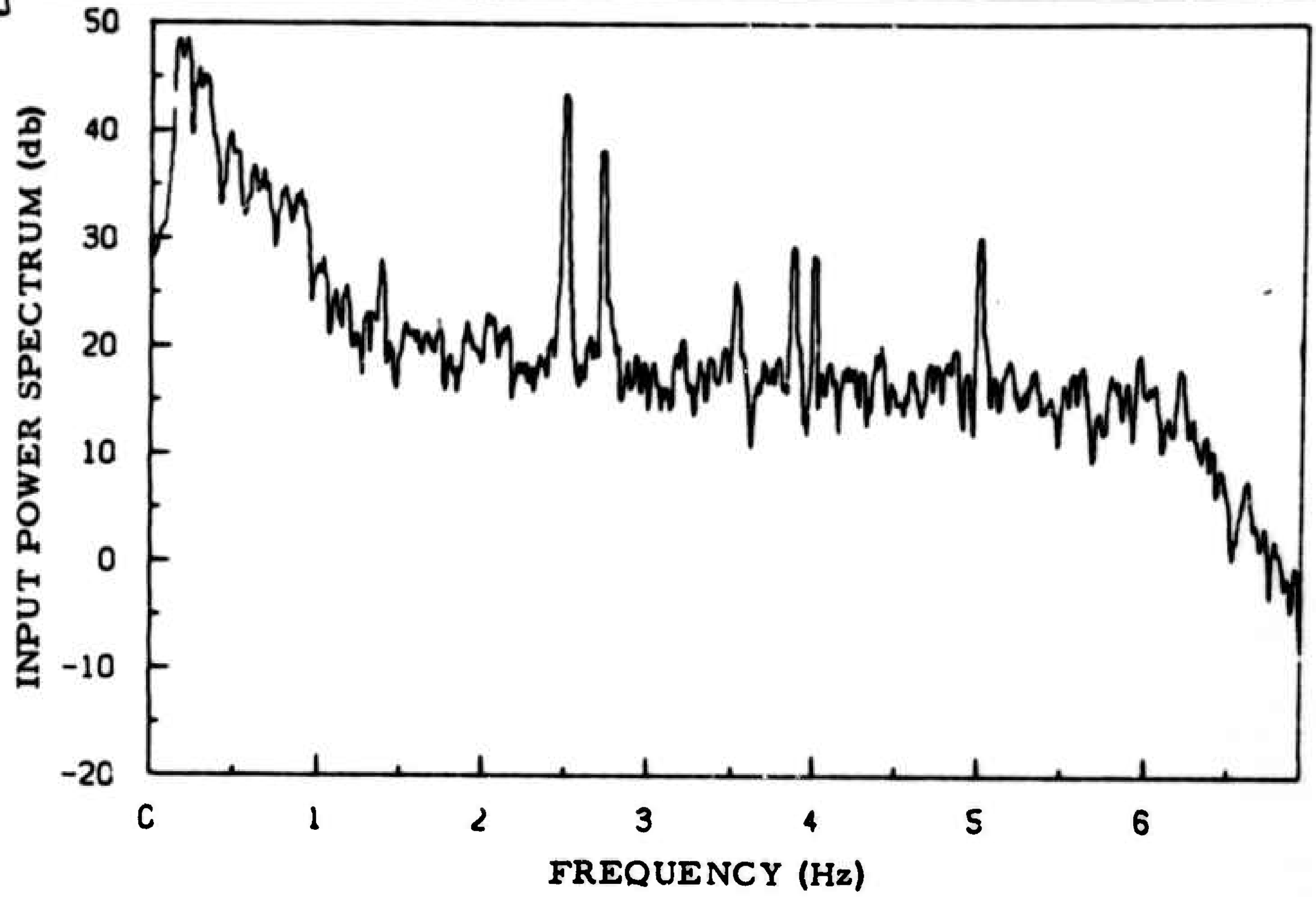

Figure III-1. Power Spectrum of Data

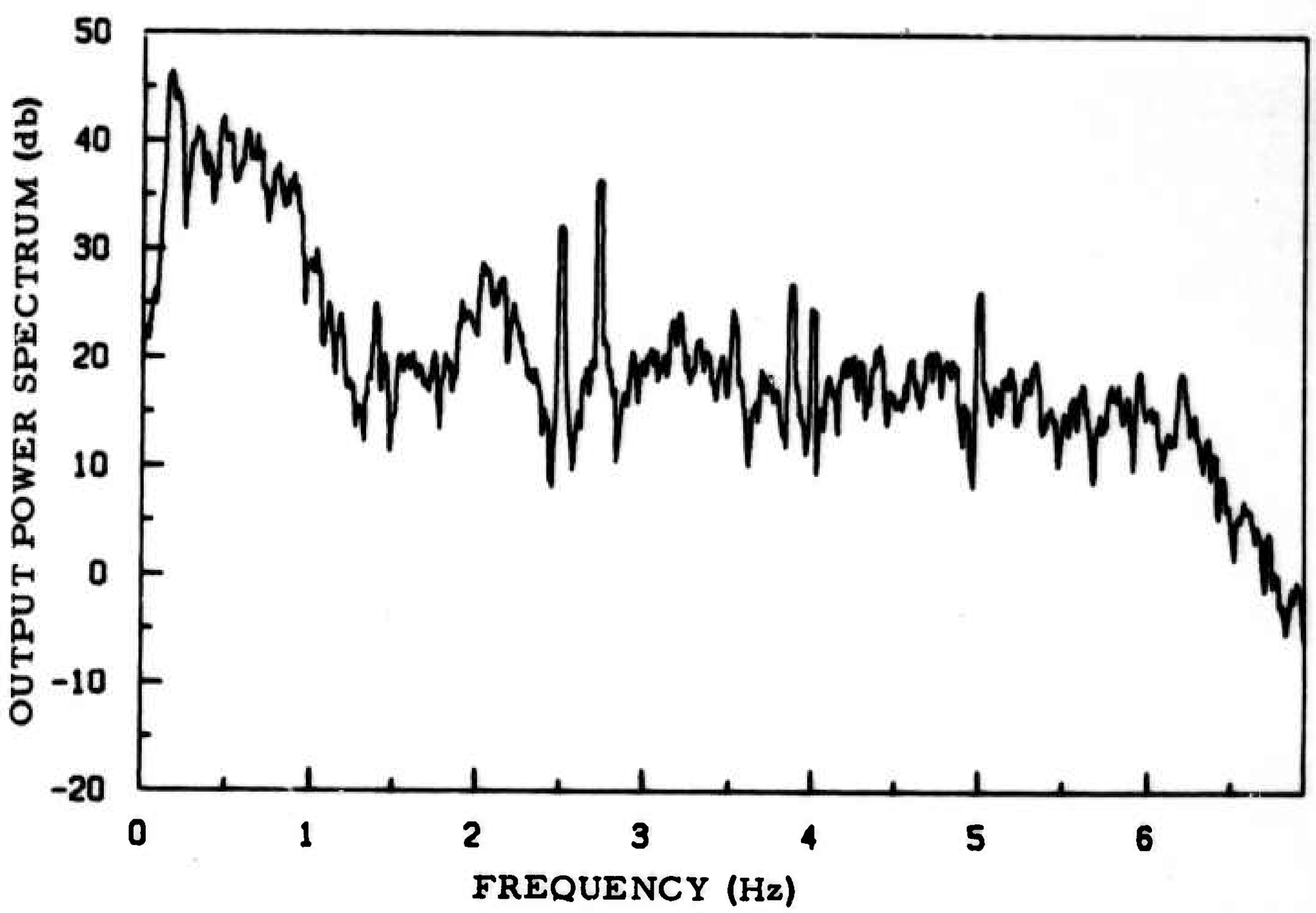

Figure III-2. Output Power Spectrum, $k_s = 0.005$, Prediction Length = 10

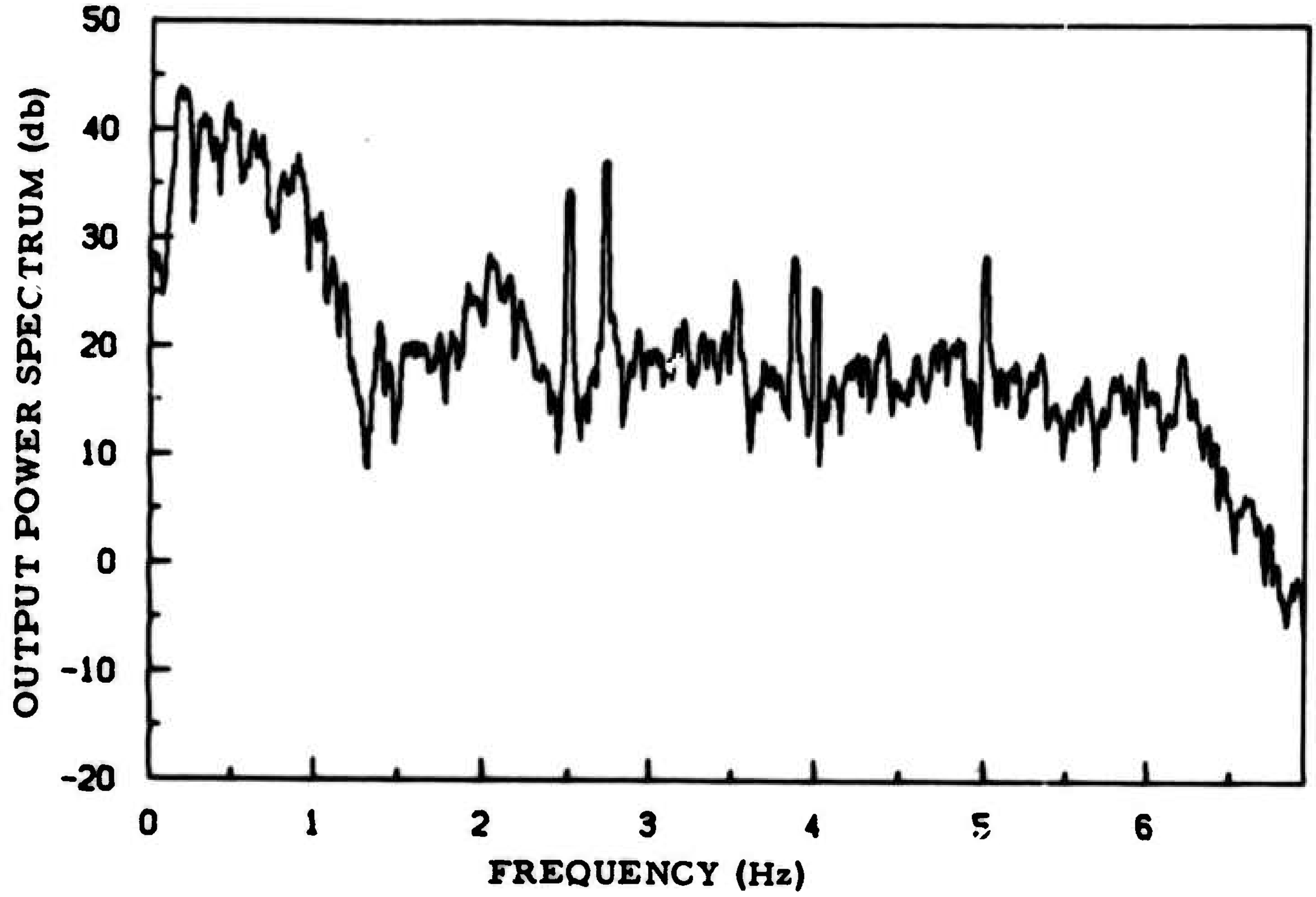

Figure III-3. Output Power Spectrum, $k_s = 0.05$, Prediction Length = 10

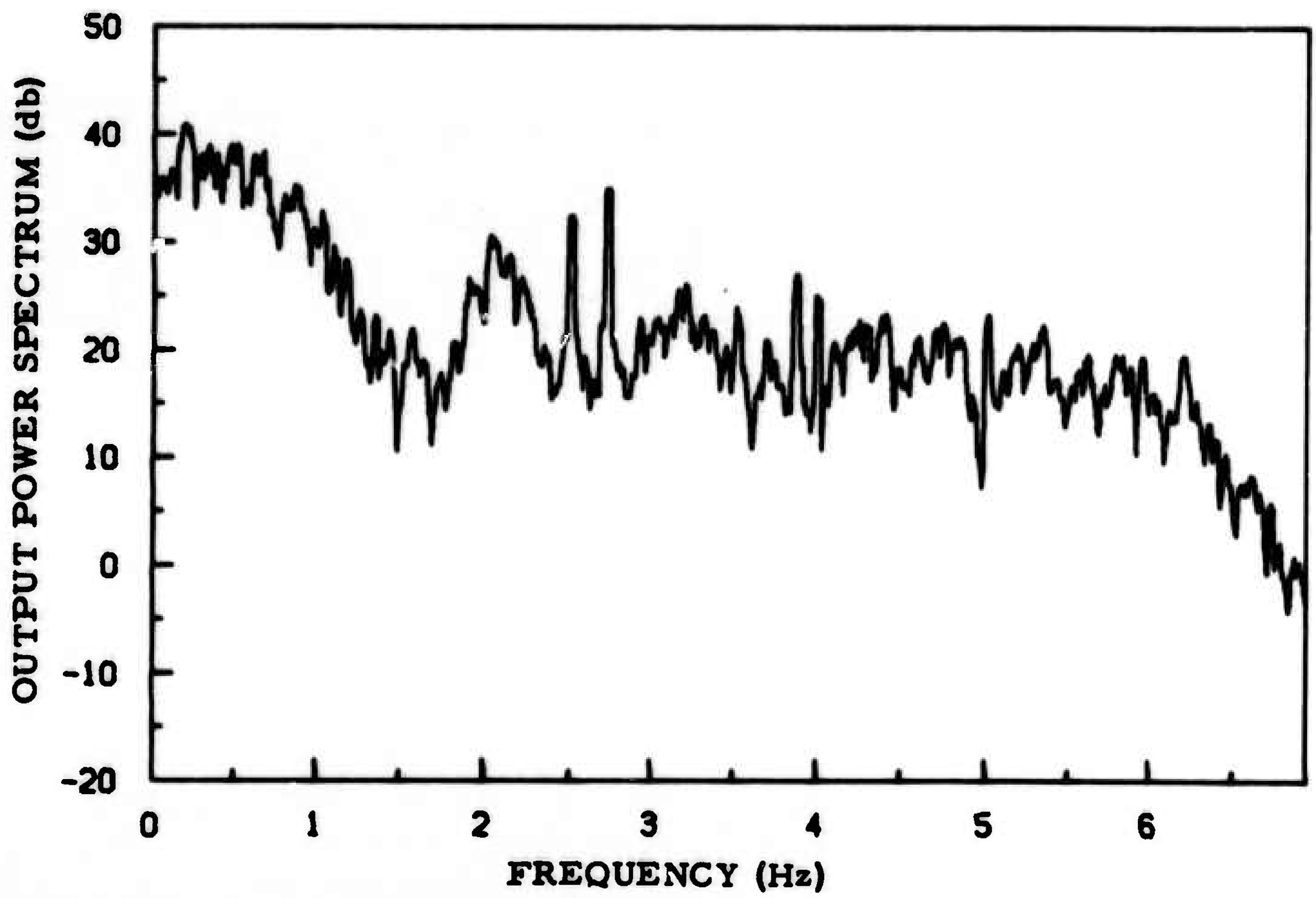

Figure III-4. Output Power Spectrum, $k_s = 0.25$, Prediction Length = 10

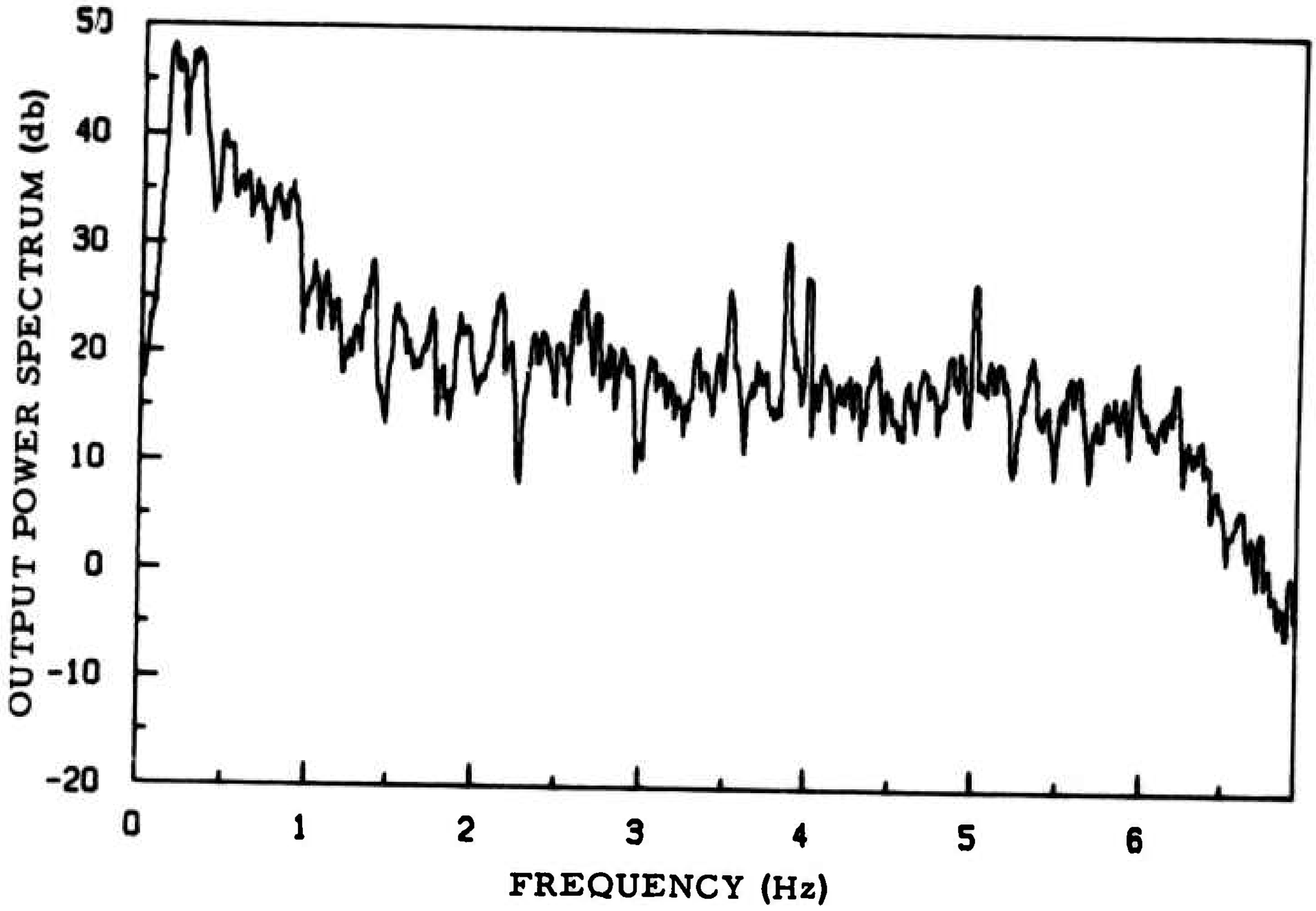

Figure III-5. Output Power Spectrum, $k_s = 0.005$, Prediction Length = 50

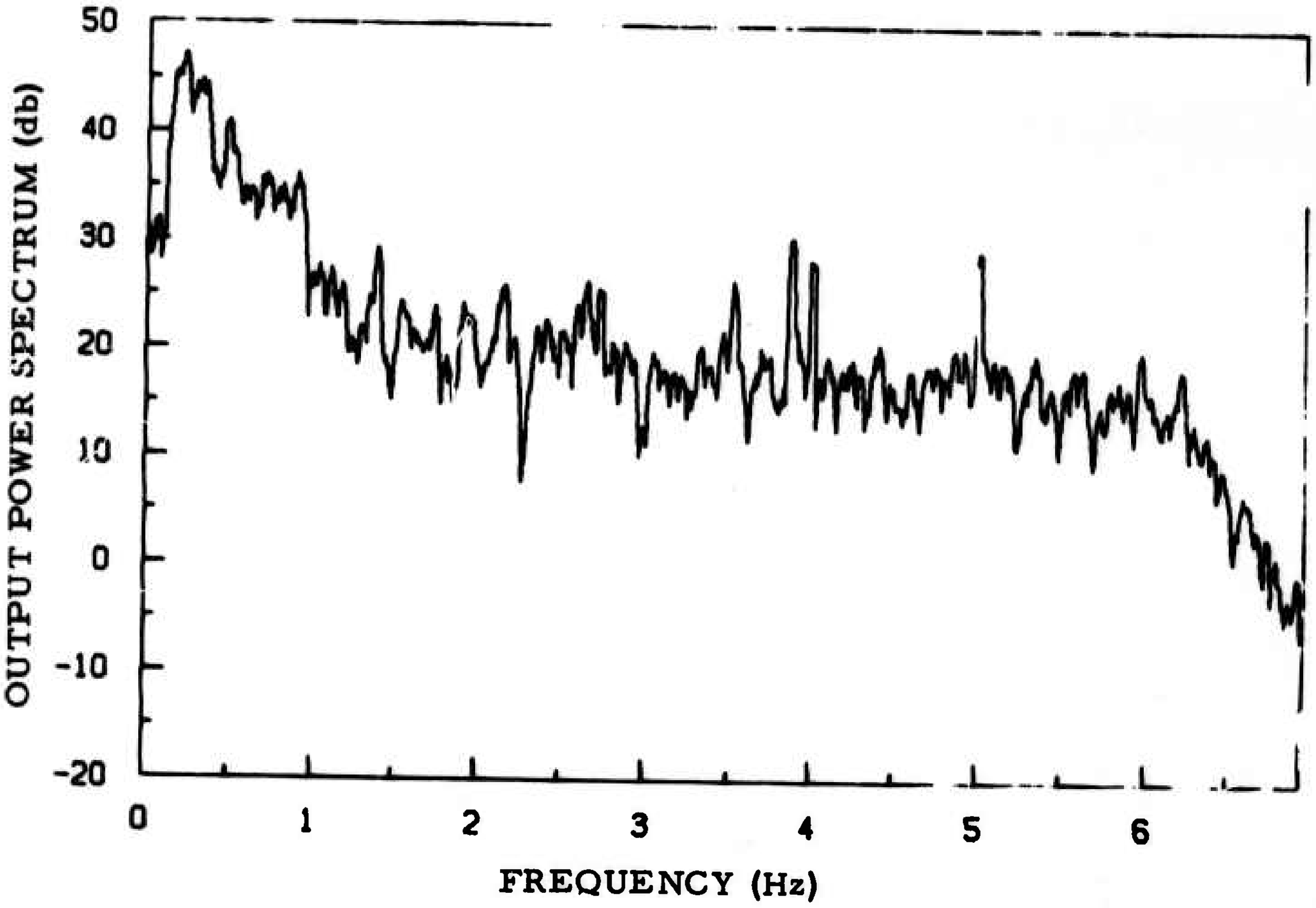

Figure III-6. Output Power Spectrum, $k_s = 0.05$, Prediction Length = 50

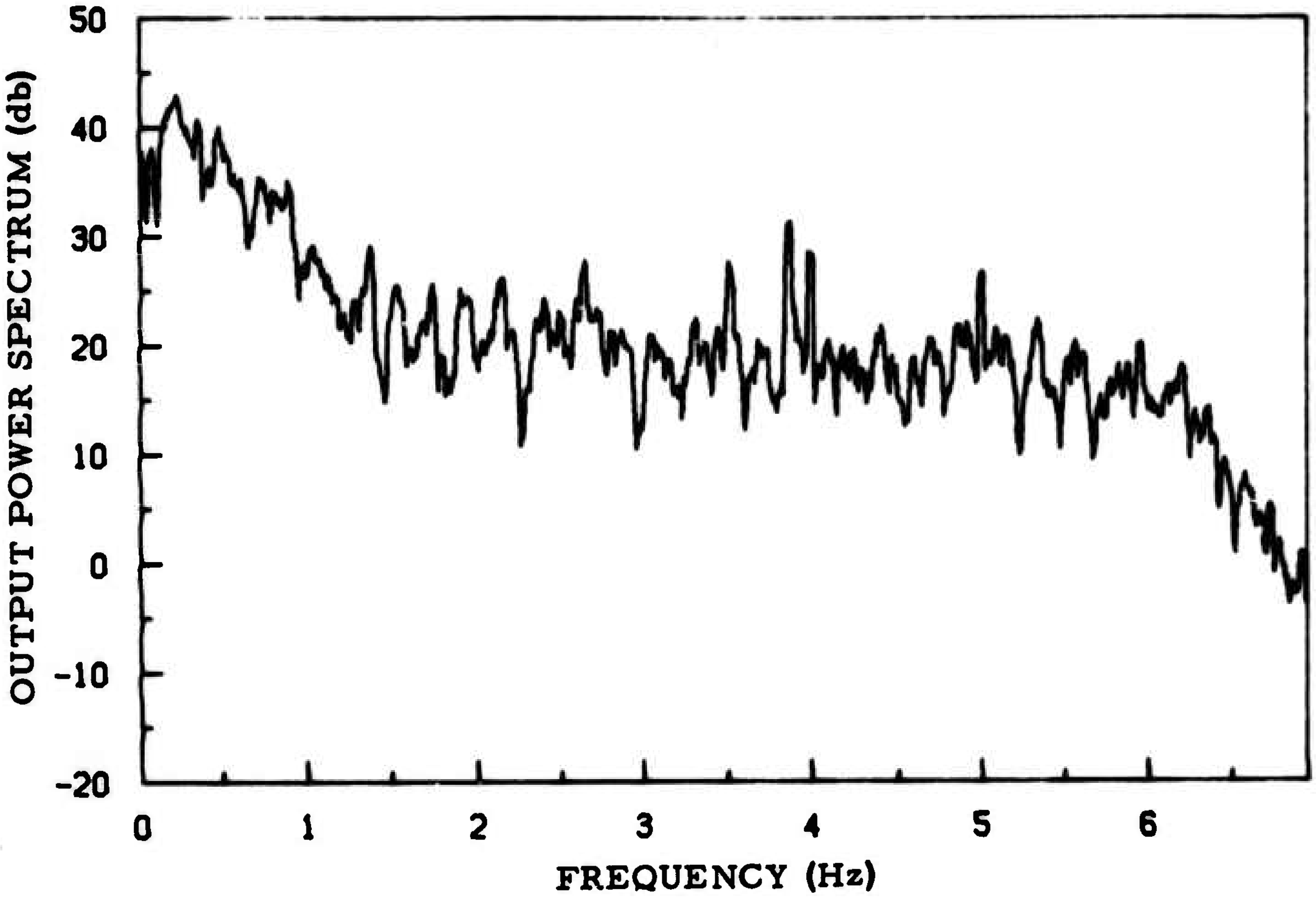

Figure III-7. Output Power Spectrum, k_s = 0.25, Prediction Length = 50

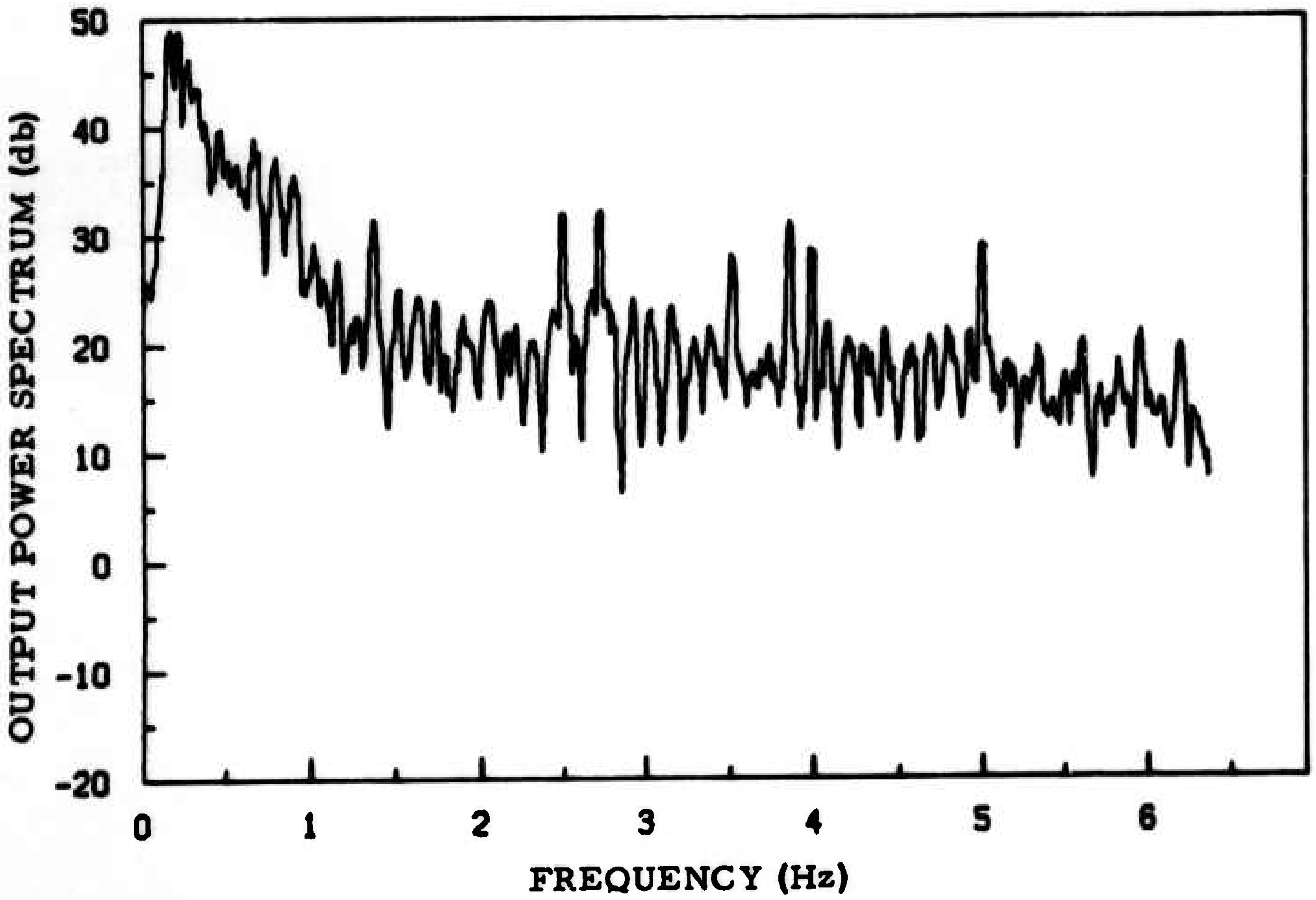

Figure III-8. Output Power Spectrum, k_s = 0.005, Prediction Length = 100

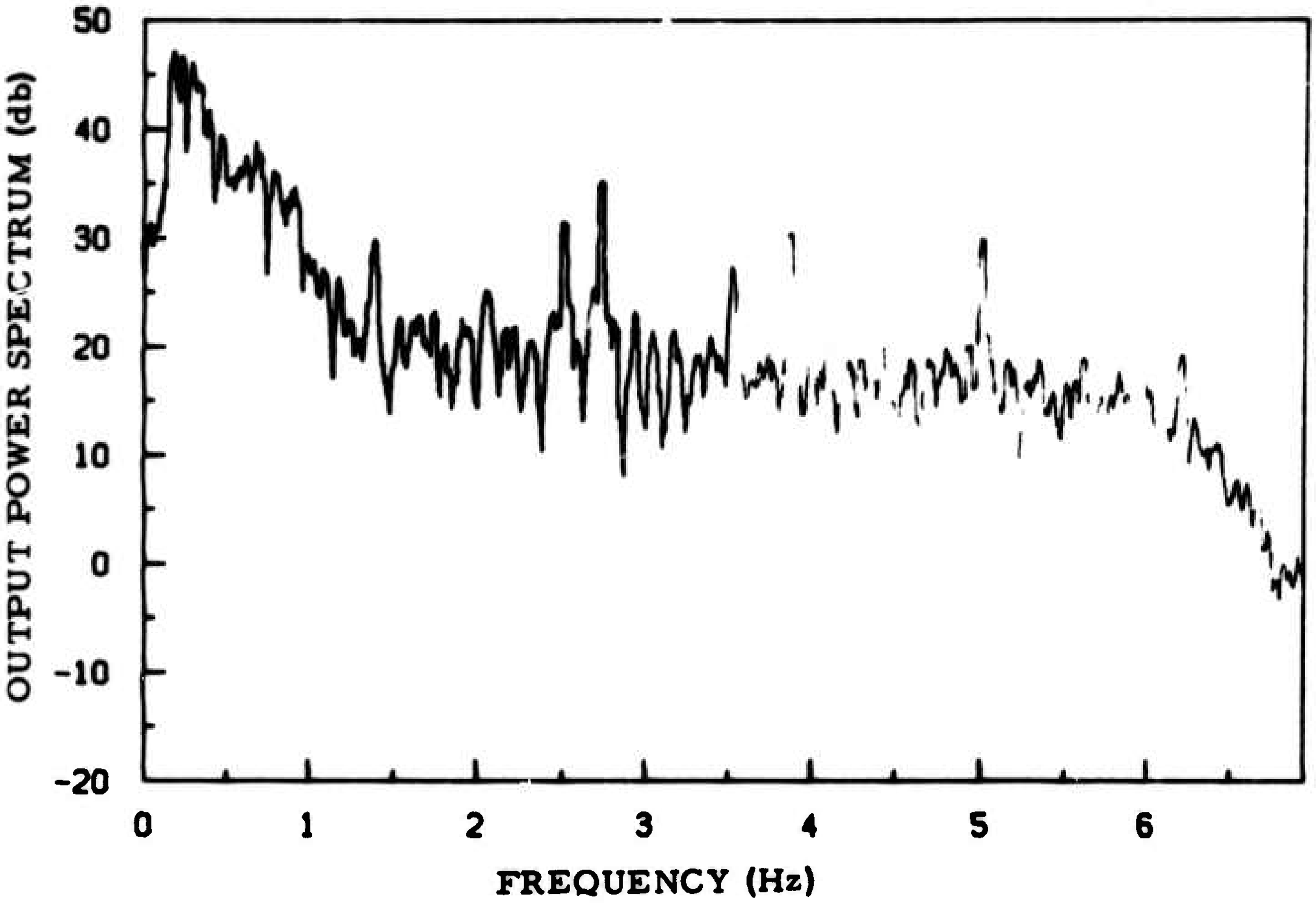

Figure III-9. Output Power Spectrum, k_s = 0.05, Prediction Length = 100

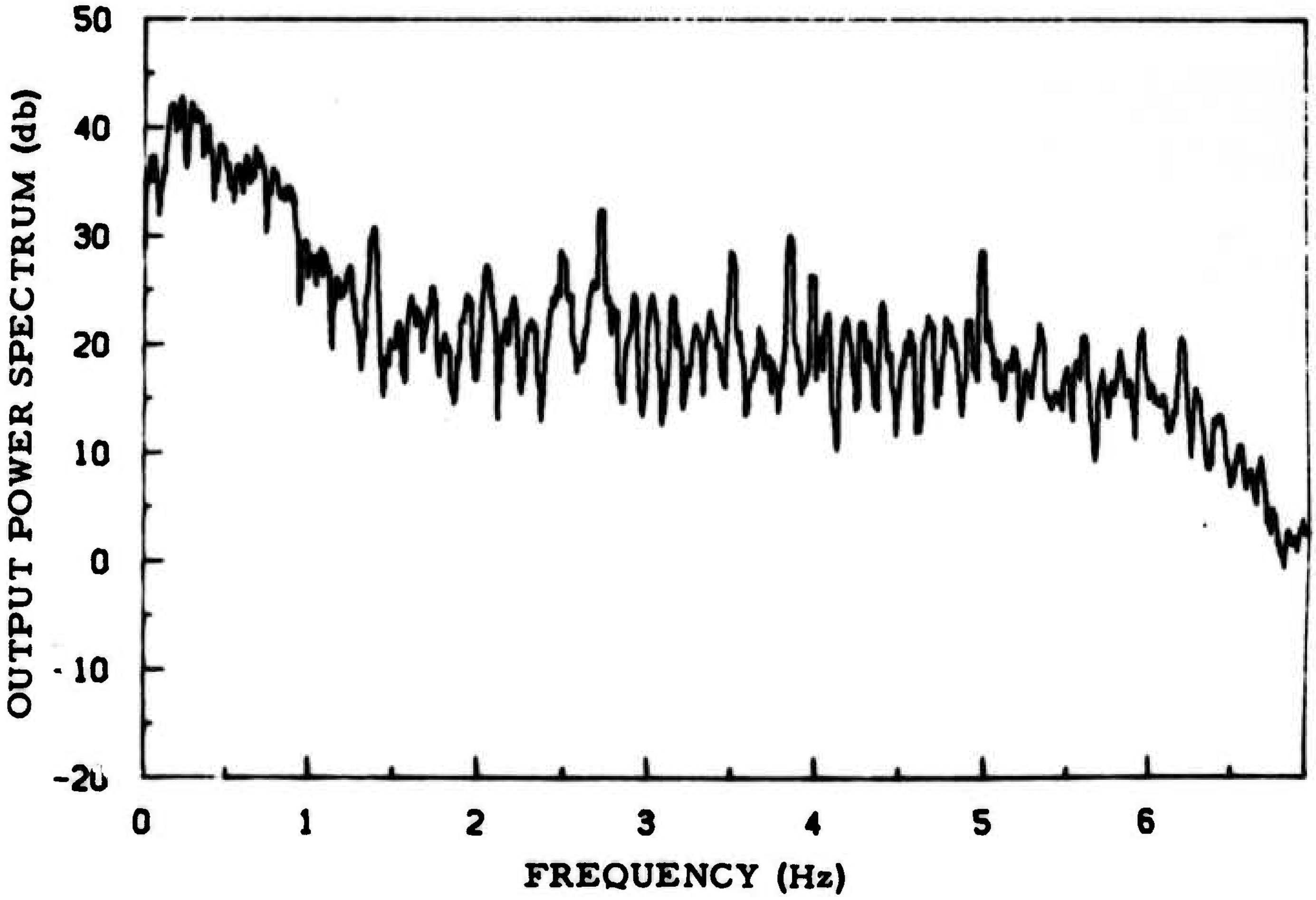

Figure III-10. Output Power Spectrum, k_s = 0.25, Prediction Length = 100

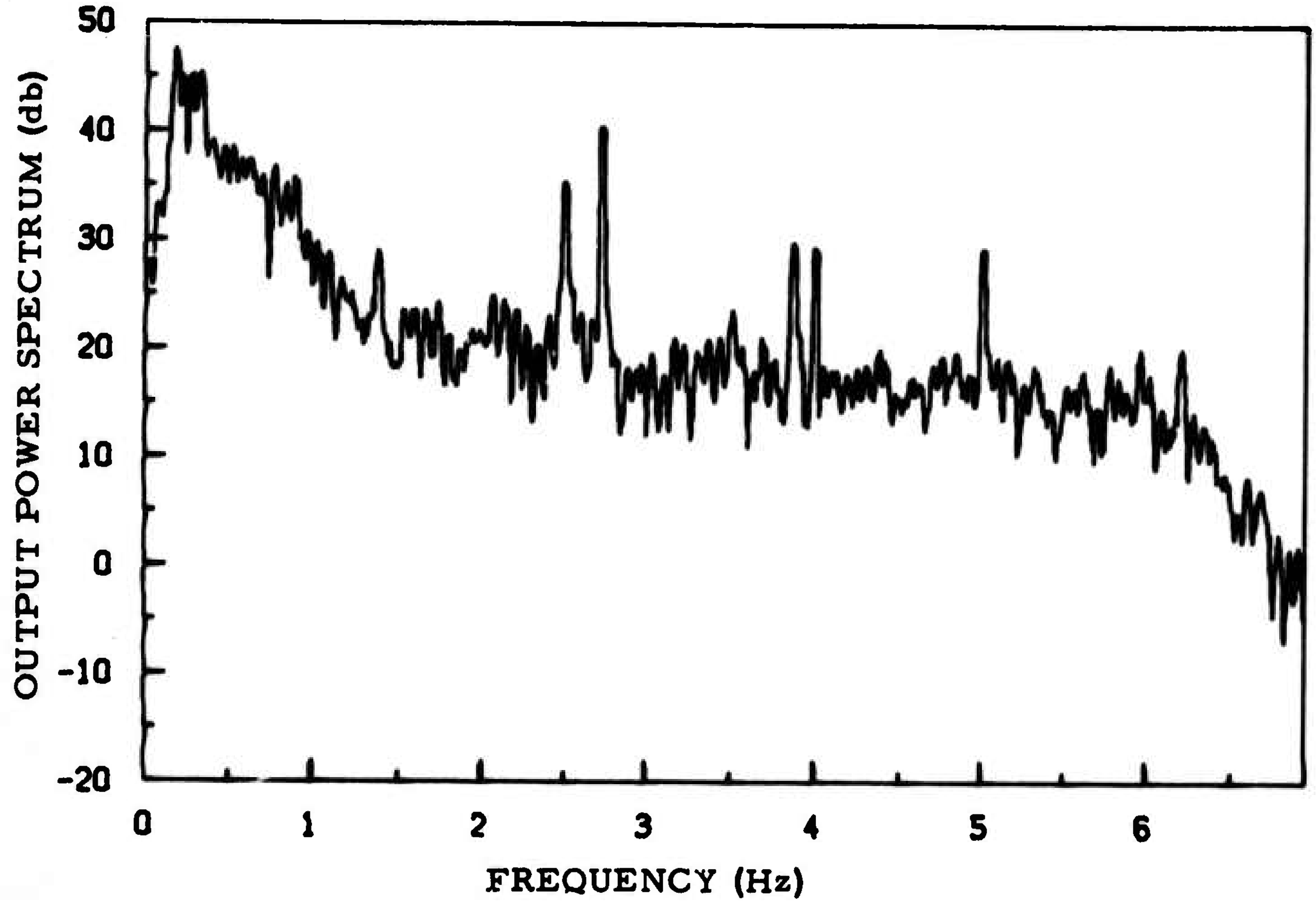

Figure III-11. Output Power Spectrum, k_s = 0.05, Prediction Length = 200

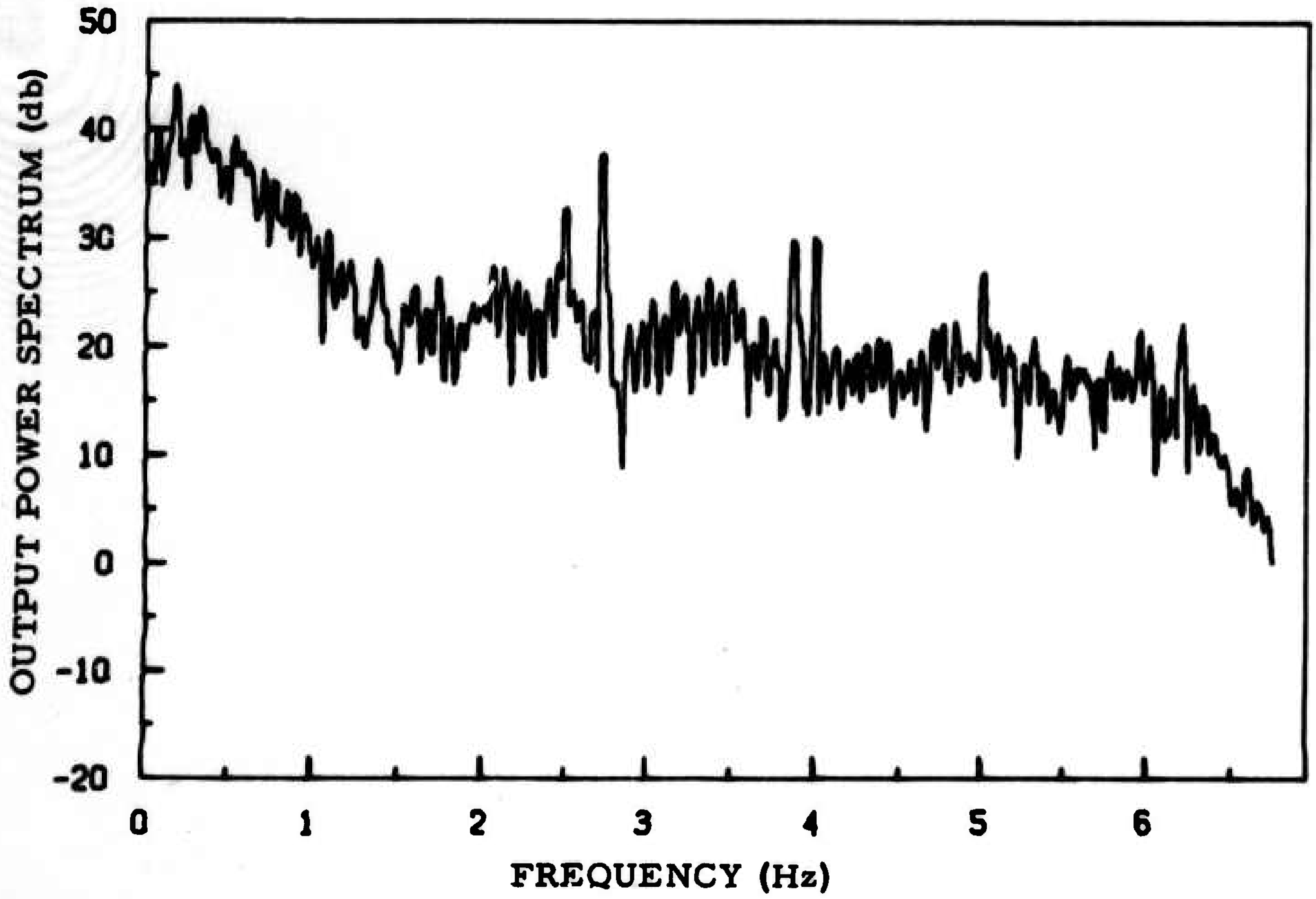

Figure III-12. Output Power Spectrum, k_s = 0.25, Prediction Length = 200

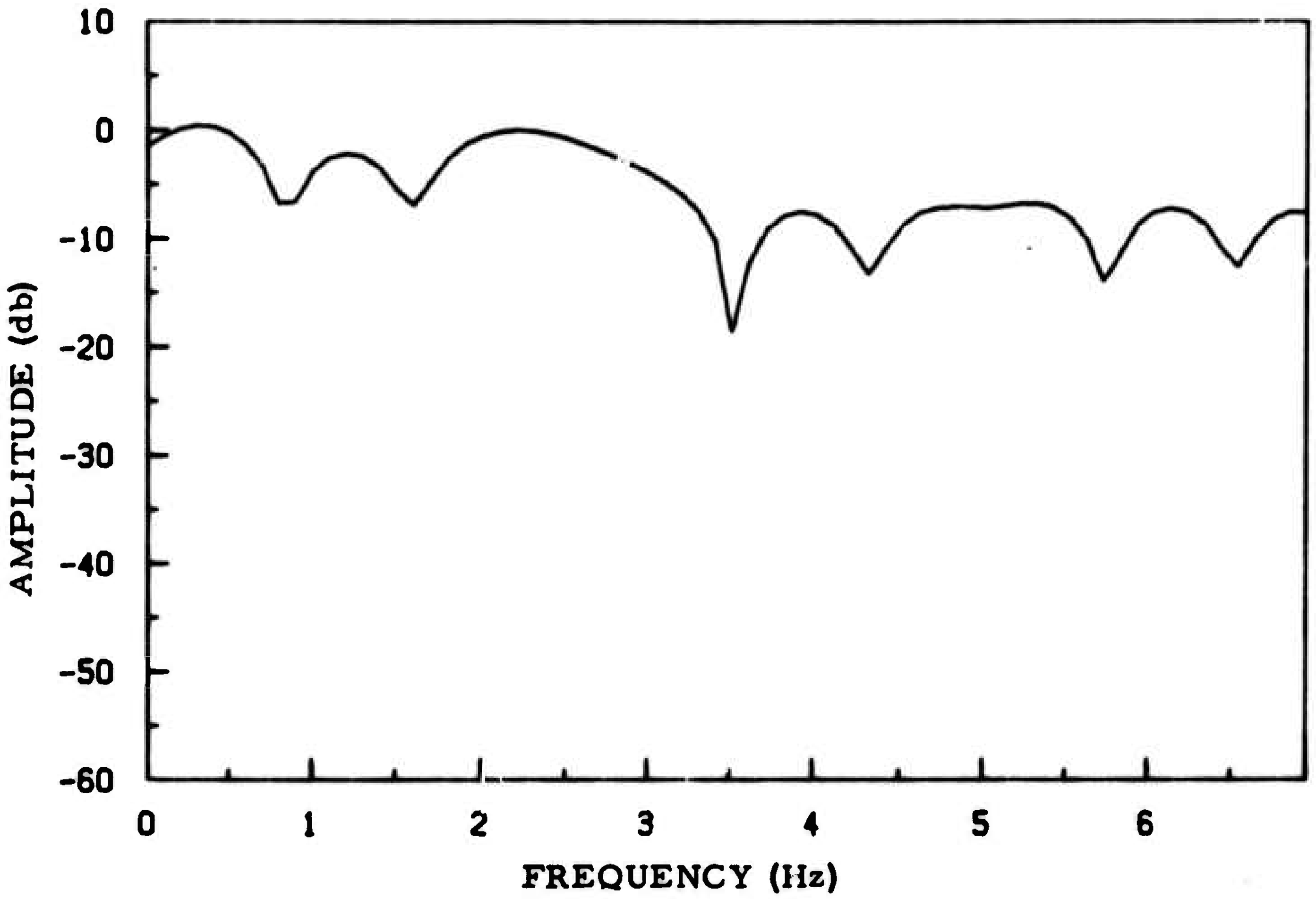

Figure III-13. Frequency Response of Terminal Adaptive Filter, k_s = 0.05, Prediction Length = 50

SECTION IV
CONCLUSIONS AND RECOMMENDATIONS

Neither of the methods examined has proved to be satisfactory in the extraction of spectral lines from seismic data. A simple method for real-time elimination of spectral lines would probably require a significant investigation. Since that is beyond the scope of the very small effort assigned to this task under the present contract, it is recommended that the study of spectral line extraction be discontinued.

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13. ABSTRACT

Two methods for the removal in real time of stable spectral lines from seismic data were investigated. The first method involved the generation of a cosine wave, by means of a digital feedback system, to approximate the spectral lines. In this method, the cosine generator is adjusted in accordance with a mean-square-error criterion. This system of adjustment was simulated and proved to be unstable. In the second method, a Widrow adaptive prediction filter is used to remove the deterministic component. A simulation of this prediction method was carried out using one seismic data channel from a short-period array. Results show that this method significantly attenuated some of the spectral lines. However, if a signal were present, some amplitude and phase distortion would be caused in the signal. In addition, this system would be cumbersome to implement.

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